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Comparing Real and Virtual Object Manipulation by Physiological Signals Analysis: A First Study

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Abstract: Virtual reality aims at reproducing reality and simulating actions like object manipulation tasks. Despite abundant past research on designing 3D interaction devices and methods to achieve close-to-real manipulation in virtual environments, strong differences exist between real and virtual object manipulation. Past work that compared between real and virtual manipulation mainly focused on user performance only. In this paper, we propose using also physiological signals, namely electromyography (EMG), to better characterize these differences. A first experiment featuring a simple pick-and-place task on a real setup and in a CAVE system showed that participants' muscular activity reveals a clearly different spectrum in the virtual environment compared to that in reality.

1 INTRODUCTION

Object manipulation has attracted much attention among other interaction tasks especially in virtual reality (VR). Obviously, object manipulation depends on environmental conditions such as the lighting, the presence of other objects and their location in the scene and so on. With the rapid development of VR for the last couple of years, reproducing high fidelity simulations in VR became a crucial issue. For instance, with the emergence of industry 4.0, simulations of manual tasks such as pick-and-place, manufacturing, handling operations are more and more frequent. These manual tasks need a precise evaluation to be validated (Fumihito and Suguru, 2012).

When it comes to simulation, VR requires technologies and methods allowing to interact with the virtual environment. Strong differences usually exist between object manipulation in the virtual and the real environments because of missing sensory feedbacks such as gravity, roughness, pressure or temperature. In this regard, a huge piece of work has been proposed in the past (Argelaguet and Andujar, 2013). Though we observe for a few years great progress in natural interfaces and interactions (Bowman et al., 2012), these techniques are still not fully mature (Mirzaei et al., 2013; Alibay et al., 2017). We still see, through newly commercialized VR headsets, that the most popular interaction interface remains based on ray tra-

cing. These devices allow easy interaction, avoiding any occlusion issues.

In this paper, we propose to compare between real and virtual object manipulation. Not only the task performance is compared but also the physiological signals that are derived from this activity are considered. We are interested in better characterizing the differences between reality and VR. As a first study, we consider a very simple yet common manual task that is pick-and-place. Indeed, we do not want to consider more complex manipulation tasks as they require much more dexterity, especially for users who are not familiar with VR, which in turn means much more parameters monitoring.

2 RELATED WORK

One strong issue in VR is to make users feel present in the virtual environment (Witmer and Singer, 1998). Early work has shown that high quality 3D graphics do not suffice to get high sense of presence. Other sensory feedback like tactile or haptic feedback showed to enhance the level of interaction (Sturman et al., 1989; Talati et al., 2005). Haptic interfaces were quickly developed to provide the sense of weight, friction, touch (see for example early devices like (Burdea, 1996; Kim et al., 2002; Koyama et al.,

2002) or more recent devices like (Ma and Ben-Tzvi, 2015; Choi and Follmer, 2016)), all challenging with imagination to provide users with realistic experience in manipulating virtual objects. The main drawbacks of such devices are: they require to be worn, meaning they are mostly intrusive, and calibration is often needed prior to be used. Léon et al. proposed a hands-on non-intrusive haptic manipulation device that allows a large variety of hand and finger configurations (Léon et al., 2016). This device is intended to simulate virtual manipulation tasks requiring high dexterity. However, the main issue is its small workspace due to the haptic arm, which may lead to repeated arm movements to move a virtual object on a large span.

Despite abundant proposals, most of these devices were not validated through comparison with object manipulation in real environments. The question of comparing real and virtual tasks is in fact not trivial. Indeed, many parameters may encounter such as the system latency, the perceived realism of the virtual scene, the available field of view, stereoscopy, and so on. Early work attempted to compare between reality and virtual reality in training situations (Kenyon and Afenya, 1995). Though the context was a little bit different than ours, results showed that virtual world-trained users were significantly more performant than untrained users but that real world-trained users did not perform significantly better than untrained users. Graham and MacKenzie compared real and virtual pointing, showing that physical pointing leads to better results (Graham and MacKenzie, 1996). However their study was conducted on a 2D interaction basis whereas here we address 3D interaction. Later work in a different context showed better performance in virtual environments and even better in mixed reality (also called dual reality) environments, compared to the one in real environments (Raber et al., 2015). However, the interaction task in virtual reality consisted in a 2D interaction on a touch screen, whereas interaction was done in 3D space in the real condition. Nevertheless, mixing reality and virtual reality seems an interesting alternative.

Several past research attempted to reduce differences between reality and VR, as in (Kitamura et al., 2002) where a manipulation method was designed by adapting reality to virtual environment constraints. However the proposed method requires constraining reality, which restricts practical usage. Chapoulie et al. proposed a framework to analyze finger-based 3D object manipulation considering several devices that were designed to be identical in both reality and VR (Chapoulie et al., 2015). Results on performance showed greater errors in virtual environments than in reality, with differences becoming more apparent as the

complexity of the devices increased. In fact they pointed out that reproducing identically real setups in virtual reality is very complex. Also they compared between wand-like and natural interfaces, showing a tendency to better results with wand-like devices. Here we do not aim at considering finger-based interaction. We will rather stick to wand-like interfaces to cope with the fact that even newly commercialized VR headsets come with such devices.

In all past work reported above, comparison between real and virtual environments have been conducted measuring user performance (such as the completion time, task errors, cognitive load through subjective questionnaires, e.g., NASA-TLX (Hart and Stavenland, 1988)). To the best of our knowledge, physiological-based parameters have hardly been considered. Electromyography (EMG) or electroencephalography (EEG) has mostly been used in human-computer interaction research work as a mean to interact with virtual contents (for example (Tisančín et al., 2014; Lotte et al., 2013)), rather than as an analysis tool of interaction tasks. Through this first study, we contribute in exploring EMG as a tool to characterize differences between real and virtual object manipulation. We consider here a simple pick-and-place task.

3 EXPERIMENT DESIGN

An experiment was designed in both a real and a virtual environments to compare user performance, user perception as well as the muscular activity during a simple object manipulation task.

3.1 Participants

10 participants were recruited on a voluntary basis within the university students to perform the experiment. No requirements regarding the level of knowledge in VR were specified when recruiting the participants. There was a briefing to give enough information about the test procedure and we collected the participants' consent to perform the experiment. No participants got compensation to the experiment. None of them were familiar with VR, however they already experienced it at least once. All were right-handed and none of them reported any health issues.

3.2 Setup

The real setup consisted in a 1.5 m-long table on which three wooden cubes ($15 \times 15 \times 15 \text{ cm}^3$ and an approximate weight of 1 kg) were arranged. Three

squared marks were drawn on the table to indicate where to place these cubes (Figure 1.b).

The setup was reproduced in a virtual environment (VE) with the same scale (Figure 1.a). We ensured consistency in the scale in the VE by superimposing a virtual cube on a real one in the virtual setup, then adjusting the size of the virtual cube manually. The virtual setup consisted in an immersive room, allowing scale-one immersion, through a home-made software based on OpenSceneGraph and VRPN (Taylor et al., 2001). The immersive room was a $3 \times 3 \times 3$ four-sided CAVE system with a 1400×1050 px resolution per side with stereoscopic vision, integrating an infrared-based tracking system to track the user's location in the CAVE and in the VE. Manipulation of the virtual cubes was performed using an ART Flystick 2 interaction device that has several buttons and a trigger. The Flystick was also tracked in position. Here we did not consider tactile or haptic feedback to avoid biases due to the intrusivity of devices incorporating such feedback.

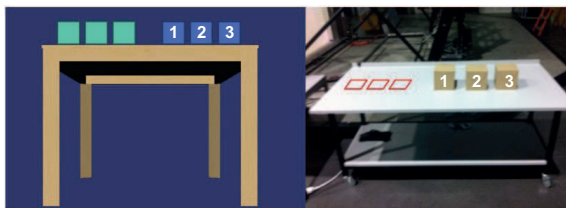


Figure 1: Object manipulation in (left) a virtual and (right) a real environments.

3.3 Tasks

As shown in Figure 1.a, the object manipulation task in the virtual environment consists in a simple pick-and-place task, that is, replacing the three blue cubes into the three green ones using the Flystick device. Selection is performed by pointing the Flystick at the center of the target cubes then pressing the trigger on the Flystick when enough close to the center of the target cube (less than 20 cm). The selected cube is then attached to the Flystick until the trigger is released. Using the trigger button allows simulating grasping. During displacement, the participant keeps pressing the trigger while positioning the selected cube. The blue cubes have to be carefully placed inside the marker cubes (the green cubes) during positioning. All three blue cubes have to be placed inside the green marker cubes in order (the first cube inside the first marker, and so on).

The same task is performed by hand in the real environment (Figure 1.b). The participant grabs the first cube, holds it up and places it inside the first

red square marked up on the left side of the table (Figure 1.b), the same task is repeated for each cube.

3.4 Muscular Activity

As the object manipulation task we consider here is a simple pick-and-place task, the active limbs are mostly the arms, with a flexion/extension movement of the elbow. The hands are also solicited to grasp the objects. Here we will not consider hand and finger movements as the aim is not to study grasping configurations, nor grasping stability. The biceps muscle was therefore considered as an appropriate place to measure the muscular activity for this task, as the biceps functions as an important flexor of the forearm, which is needed to pick and place objects.

To measure the muscular activity, we use three-lead wireless BIOPAC surface electromyography (sEMG) sensors¹. The sensors are connected to an amplifier and an acquisition stand via wireless connection, allowing wireless data logging by a PC. The EMG signal data are transmitted at a rate of 2 kHz, providing a high resolution wireless EMG waveform at the receiver's output.

The positive and negative leads were placed at the origin and end of the biceps muscle respectively and the ground lead right on the elbow. As the arm can be either opened, semi-opened or closed, we ensured stable and solid positioning of the sensors on the arm regarding body temperature variation and movement tension to get robust and meaningful signals.

3.5 Procedure

Each participant followed the procedure below:

1. Three BIOPAC sensors were placed on the participant's right arm as described in the previous section.
2. The participants were asked to lift off the three cubes one by one from the right side of the real table, to move them in a semi-circular path to trigger flexion of the elbow and to precisely place them on the three red squared marks on the left side of the table.
3. An EMG signal was recorded during this task. This measurement was considered as a reference measurement.
4. The participants were then introduced to the CAVE system. They were briefly explained how to use the Flystick and were able to train for two minutes.

¹<https://www.biopac.com/application/emg-electromyography/>

5. The participants had to pick the virtual blue cubes, to move them in a semi-circular path and to place them in the green cubes trying to be as precise as possible.
6. An EMG signal was recorded during this task.

Throughout the experiment, the time of task completion was recorded in both environments.

At the end of the experiment, a presence questionnaire (Witmer and Singer, 1998) was filled out by the participants. We also asked the participants' preference between manipulation in the real and the virtual environments. The presence questionnaire and EMG are used here as psychological (subjective) and physiological (objective) measurements respectively.

The participants took less than 10 minutes to complete the whole experiment.

3.6 Object Manipulation Evaluation Criteria

We propose three criteria to evaluate object manipulation. The length of the movement, ϕ_1 , the amount of rotation, ϕ_2 , and the completion time, t , are considered as time space features for the comparison between the real and the virtual environments (1).

$$\text{criteria} = \{\phi_1, \phi_2, t\} \quad (1)$$

3.6.1 Criteria 1: The Length of the Object Movement Trajectory (ϕ_1)

The first feature is the length of the movement, which is a criterion to assess a given task (selection, movement and placement of a cube) in different environments. Besides, it can be used to compare a manipulation mechanism or to compare the same task in two different environments. As a result, the longer the length of the movement, the harder the task. The movement in the real environment is considered as a semi-circular path with an average radius (\bar{r}) and an average length $\pi\bar{r}$. Theoretically, the length of a given continuous curve is calculated by (2) in 3D space.

$$\phi_1 = \int_a^b \left(\sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2} \right) dt \quad (2)$$

Equation (2) can be easily substituted by (3) for a curve with sampled data with $\Delta t = 1$ s.

$$\phi_1 = \sum_{i=1}^{n-1} \|\Delta P_i\| \quad (3)$$

$$\|\Delta P_i\| = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2}$$

where n indicates the number of points along the path.

3.6.2 Criteria 2: The Amount of Rotation (ϕ_2)

The amount of rotation along the circular path in a plane is defined by (4) as specified in (Tai, 1986).

$$\nabla \times F = \oint_0^{2\pi} \vec{F}(x, y, z) d\vec{r} \quad (4)$$

where F is the movement trajectory. Since the movement is semi-circular, (5) and (6) are used to calculate the amount of rotation for a continuous and a discrete functions respectively.

$$\nabla \times F = \int_0^\pi \vec{F}(x, y, z) d\vec{r} \quad (5)$$

$$\begin{aligned} \nabla \times F = & - \sum_{i=1}^{n-1} \left(\frac{(x_{i+1} - x_i) \cos(\theta) \cos(\phi)}{\|\Delta P_i\|} \right) \\ & - \sum_{i=1}^{n-1} \left(\frac{(y_{i+1} - y_i) \cos(\theta) \sin(\phi)}{\|\Delta P_i\|} \right) \\ & + \sum_{i=1}^{n-1} \left(\frac{(z_{i+1} - z_i) \sin(\theta)}{\|\Delta P_i\|} \right) \end{aligned} \quad (6)$$

where θ and ϕ represent the parameters of the sphere coordinates. x_i, y_i, z_i are the coordinates of the i^{th} point P on curve F and n represents the number of points on F . We assume that the reference semi-circular path lies on the XZ plane (the vertical plane on which the cubes lie), meaning $y = 0$ and $\phi = 0$. Moreover, the resolution of θ is chosen as $\frac{\pi}{n}$ for simplicity. As a result, (6) can be rewritten as (7). Using (7) the total rotation along the path can be calculated.

$$\begin{aligned} \nabla \times F = \phi_2 = & - \sum_{i=1}^{n-1} \left(\frac{(x_{i+1} - x_i) \cos\left(i\frac{\pi}{n}\right)}{\|\Delta P_i\|} \right) \\ & + \sum_{i=1}^{n-1} \left(\frac{(z_{i+1} - z_i) \sin\left(i\frac{\pi}{n}\right)}{\|\Delta P_i\|} \right) \end{aligned} \quad (7)$$

4 RESULTS

4.1 Data Analysis in the Time Domain

4.1.1 Length of the Movement Trajectory

By applying (3) the length of the performed movement can be calculated for each cube. The results of this calculation are shown in Figure 2 left.

A paired Student t-test provided a significant difference between the length of the average movement

in the virtual ($M = 1.19$ m, $SD = 0.28$) and the real ($M = 0.68$ m, $SD = 0.05$) environments ($p = .039$, $t(9) = 5.41$). Besides, we performed a one-way ANOVA test to be sure that the differences between each cube displacement were not significant in both environments, which was indeed the case ($p = .141$).

4.1.2 Amount of Rotation

The amount of total rotation can be calculated by (7). The results of this calculation are shown in Figure 2 right. A comparison between both environments showed that in the virtual environment this value is significantly higher than in reality ($p = .0035$).

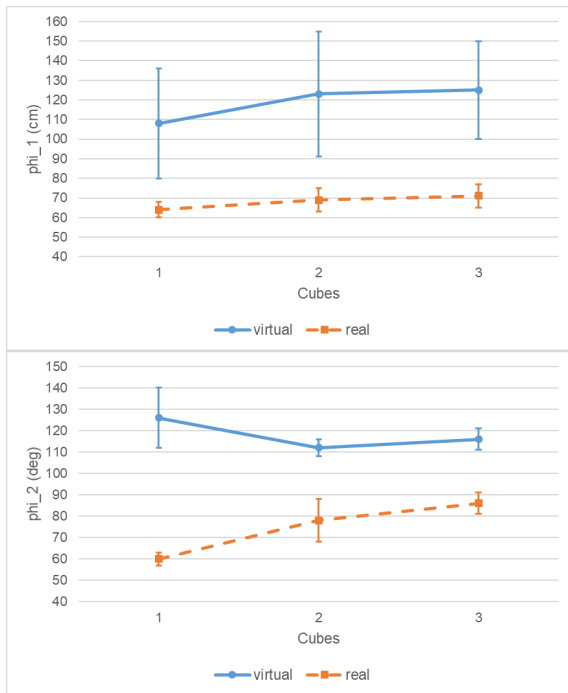


Figure 2: Length of the movement trajectory (top) and amount of rotation (bottom) in the virtual (blue) and the real (orange) environments for the three cubes with the order shown in Figure 1.

4.1.3 Completion Time

Figure 3 shows the time taken to complete the manipulation task both in the virtual (black) and the real (gray) environments. A paired Student t-test provided a significant difference between the time of completion in the virtual ($M = 79.78$ s, $SD = 43.20$) and the real ($M = 24.16$ s, $SD = 5.095$) environments ($p = .0026$, $t(9) = 3.62$). Therefore, the participants spent more time in the virtual environment than in the real one ($M_v = 79.78 > M_r = 24.16$) to complete the manipulation task. Moreover, the variation in the

virtual environment is much larger ($SD_v = 43.20 > SD_r = 5.095$) than in the real environment.

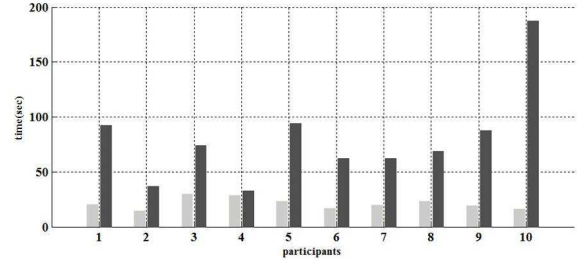


Figure 3: Time of task completion in the real and the virtual environments.

4.1.4 EMG Signal

An example of a logged EMG signal in the time domain is shown in Figure 4. We can observe a clear difference between the real and the virtual environments. As shown on the top signal, three activities corresponding to the displacement of the three cubes can be distinguished (separated by the red bars) in the real environment while in the virtual environment the activities (bottom signal) are not easily distinguishable, although the tasks in both environments are close to each other. This is the only information we can get in the time domain. There are high and low components in the signal that can hardly be differentiated.

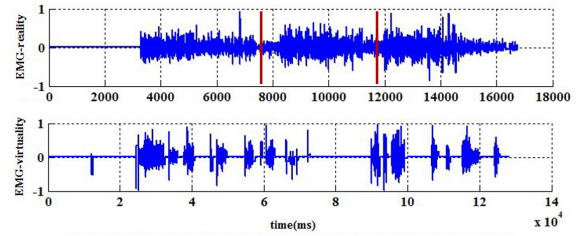


Figure 4: EMG signals recorded in the real (top) and the virtual (bottom) environments for one participant.

4.2 Data Analysis in the Frequency Domain

Because the time representation of the EMG signals does not provide clear clues on the muscular activity, especially in the virtual environment, the recorded EMG signals are converted to the time-frequency space (Boashash, 2003).

Figure 5 shows the time-frequency representation of the EMG signal for three participants. Red colors indicate frequency components with high power while blue colors indicate frequency components with very low power. From this representation, activities can be clearly distinguished in the real environment,

with three sets of components corresponding to the displacement of the three cubes. Most of high power components are below 100 Hz, which corresponds to normal muscle activities (Sadoyama and Miyano, 1981). Whereas in the virtual environment, we can observe much more components with lower power, which supposes more movements with smaller amplitude of the biceps.

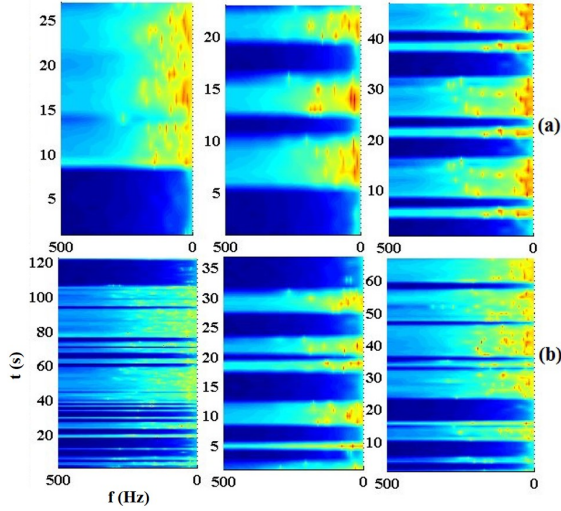


Figure 5: Time-frequency representation of the EMG signal in the (a) real and the (b) virtual environments for three participants.

4.3 Questionnaire Data Analysis

First, we asked the participants to rate the level of their satisfaction in both environments on a 7-point Likert scale (Figure 6). As seen, the highest rate has been given to the real environment, in average 5.9. A paired Student t-test showed a significant difference between the real ($M = 5.9$, $SD = 1.17$) and the virtual ($M = 4.5$, $SD = 1.19$) environments ($p = .0013$, $t(9) = 3.45$).

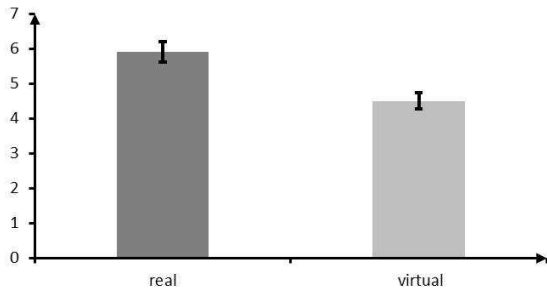


Figure 6: Level of satisfaction in both environments.

Then, from the presence questionnaire, the control (CF), sensory (SF) and distraction (DF) factors

were calculated as three main factors with the correction factor proposed by Witmer and Singer (Witmer and Singer, 1998). The results of the calculation are shown in Figure 7. In average, the score associated with CF and SF is higher than DF. From a paired Student t-test, CF ($M = 7.049$, $SD = 1.32$) and SF ($M = 5.93$, $SD = 1.37$) are significantly higher ($p = 2.71 \times 10^{-6}$, $t(9) = 4.32$ and $p = .0009$, $t(9) = 3.75$, respectively) than DF ($M = 3.9$, $SD = 0.79$).

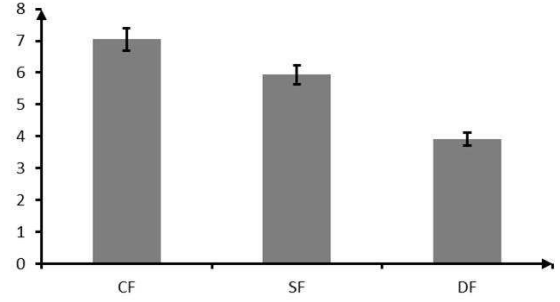


Figure 7: Sub-scores provided by the presence questionnaire in the virtual environment.

5 DISCUSSION AND LIMITATIONS

From the results, the participants spent more time with larger movements in the virtual environment than in the real one ($\cong 3$ times), which shows object manipulation in the virtual environment is harder than in the real environment. One reason lies in the fact that we did not provide any tactile or haptic feedback to the participants in the virtual environment, which confirms past work on the importance of adding other sensory cues than just visual feedback. Another reason may lie in the choice of participants who were not familiar with VR. Further experiments should be conducted with VR users.

Also we observed a much larger variation of the length of the movement trajectory in the virtual environment than in reality. This huge difference, 9 times, originates from different training experiences. None of the participants experienced virtual object manipulation in the near past. However, surely they experienced similar object manipulation tasks in real environments. Since the participants did not have the same experience in the virtual environment, they recalled their experience from the real environment. Because there is a strong difference in terms of sensory input to the cortex between the real and the expected inputs, the calculated motor command in the brain either is overestimated or underestimated which in turn creates a large deviation from the mean value in the vir-

tual environment. Again, other experiments should be conducted with VR users to see whether these differences of variation tend to decrease.

Regarding EMG, we see a clear difference of muscular activity between the real and the virtual environments. The time-frequency representation of the EMG signals showed much more components with lower power in the virtual environment. Indeed, in the real environment, complete feedbacks (visual, tactile, sound) are provided by the sensory organs to the brain, consequently the brain can recall the appropriate pattern and generate accurate motor commands to the muscles. In the virtual environment, some sensory information is missing; as a result the brain cannot extract the appropriate pattern and therefore, it cannot generate very accurate motor commands to the muscles. Typically, the participants performed several times small flexion/extension movements of their forearm to precisely position the cubes in the virtual environment.

Here, we considered real cubes of approximately 1 kg whereas the Flystick weighs around 300 g, which may have affected the measurements. Unrealistic texture rendering in the virtual condition may also have influenced movements as past work showed texture to have an influence on weight perception (Flanagan et al., 1995). Further experiments should be done with exactly the same conditions in both environments.

Another limitation of our study is that in the virtual condition, the participants had to hold the Flystick all the time, even when they did not grasp any virtual cube, which could bias the comparison with the real condition. Though EMG signals were provided from the biceps thus without any link with hand movements, further investigation should be carried out to verify this aspect, using for example optical-based hand trackers.

Looking at subjective data, the presence questionnaire revealed that the control and the sensory factors were much higher than the distraction factor. It means the user interface was well designed for an object manipulation task in virtual environments, was not distractive and was capable to involve several sensory inputs. To verify this claim, we have compared DF with the participants involvement (INV). A paired Student t-test showed INV ($M = 3.9$, $SD = 0.785$) to be significantly higher than DF ($M = 5.75$, $SD = 1.64$) ($p = .0038$, $t(9) = 3.95$) as shown in Figure 8.

Finally, as other sensory cues were missing in the virtual environment, not surprisingly, the participants preferred object manipulation in the real environment than in the virtual one, with a level of satisfaction significantly higher in the real condition than in the virtual one. Investigation should be made to determine

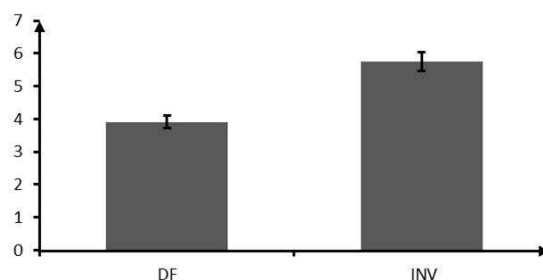


Figure 8: Level of distraction and involvement in the object manipulation task in the virtual environment.

the role of the interaction technique, apart from the effect of multi-sensory cues, as in the virtual condition we imposed an interaction strategy, whereas in the real condition, the participants were free to choose their own grasping strategy.

6 CONCLUSION

We evaluated through a first study a simple manipulation task using EMG and objective criteria, and compared a real and a virtual environment situations. EMG signals revealed clear differences between the real and the virtual environments, and time space features showed the virtual condition to require more arm movements than in the real condition. These differences originated from a gap between the actual and the expected sensory inputs to the brain. As virtual reality aims at reproducing real situations, characterizing differences between the real and the virtual environments could help better design interaction devices and methods, so that user experience can be enhanced in virtual environments and be close to real manipulation tasks.

Future work will include in-depth investigation with more participants accustomed to VR and different object manipulation techniques closer to real manipulation, e.g., using finger trackers that do not require holding any device all the time. We will also consider tactile/haptic feedback and see how physiological signals behave accordingly, knowing that past research showed tactile feedback to enhance interaction in virtual environments.

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